

NA61-SHINE: HADRON PRODUCTION MEASUREMENTS FOR COSMIC RAY AND NEUTRINO EXPERIMENTS.

N. ABGRALL

on behalf of the NA61 and T2K collaborations.

*Département de Physique Nucléaire et Corpusculaire - DPNC, 24 quai Ernest Ansermet,
1205 Genève, Switzerland*

As neutrino long baseline experiments enter a new domain of precision, important systematic errors due to poor knowledge of production cross-sections for pions and kaons require more dedicated measurements for precise neutrino flux predictions. The cosmic ray experiments require dedicated hadron production measurements to tune simulation models used to describe air shower profiles. Among other goals, the NA61-SHINE² (SPS Heavy Ion and Neutrino Experiment) experiment at the CERN SPS aims at precision measurements (5% and below) for both neutrino and cosmic ray experiments: those will improve the prediction of the neutrino flux for the T2K¹ experiment at J-PARC and the prediction of muon production in the propagation of air showers for the Auger³ and KASCADE⁴ experiments. Motivations for new hadron production measurements are briefly discussed. NA61-SHINE took data during a pilot run in 2007 and in 2009 with different Carbon targets. The NA61-SHINE setup and preliminary spectra for positive and negative pions obtained with the 2007 thin (4% interaction length) Carbon target data are presented. The use of the NA61 data for the T2K neutrino flux predictions is finally discussed in further details.

1 Needs for new hadron production measurements

Many hadron production experiments have been conducted over a range of incident proton momenta from 3 GeV/c to 450 GeV/c. However, most of them cover only limited ranges in momentum p and production angle θ (or Feynman scaling variable x_F and transverse momentum p_T).

Several models of secondary production have been derived by fitting and interpolating experimental data on $p+A \rightarrow \pi^\pm X$ or $p+A \rightarrow KX$. Shower cascade models (e.g. MARS⁶, FLUKA⁸) contain a number of physical assumptions and cannot be modified by users. Parametrizations (e.g. Sanford-Wang⁹, Malensek¹⁰) account for various aspects of production cross-sections such as p_T -scale breaking but do depend on the nuclear target properties, re-interactions, etc.

The lack of hadron production data requires reliance on such models to extrapolate from existing data to the conditions of a given experiment. These extrapolations imply large and poorly known systematic uncertainties. Muon and neutrino flux predictions for current and projected cosmic ray and neutrino experiments will require a precision better than that obtained from those extrapolations. New hadron production data at required projectile momentum and with relevant targets are mandatory to reach the goals of those experiments.

2 The NA61-SHINE measurements

2.1 The NA61-SHINE experimental setup

The NA61-SHINE apparatus⁵ (see Fig. 1) is a large acceptance spectrometer which consists in a set of five time projection chambers (TPCs): two TPCs, referred to as vertex TPCs, are embedded in dipole magnets (1 Tm) and provide a high momentum resolution, while two larger TPCs (main TPCs) are placed downstream out of the magnetic field region. A smaller TPC, referred to as GAP TPC, is placed in between the two vertex TPCs. This set of TPCs is complemented by an upgraded time-of-flight (*ToF*) system with 120 and 70 ps resolution for the forward and left/right walls respectively.

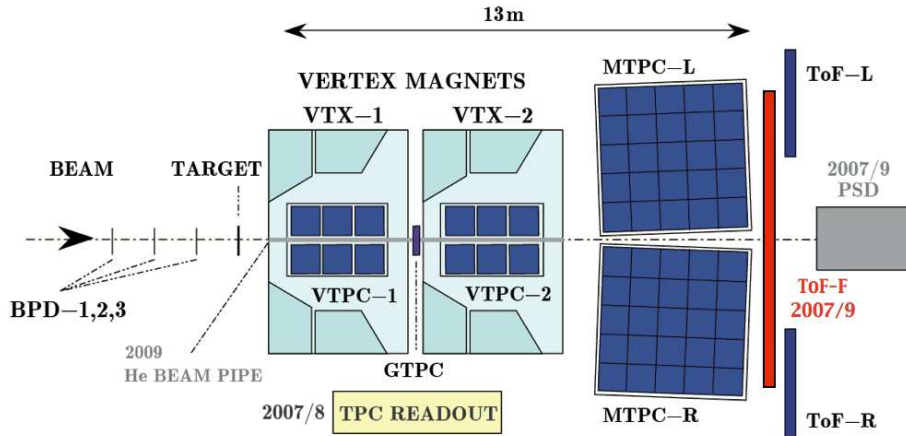


Figure 1: The NA61-SHINE apparatus. Dates refer to different installation periods and upgrades.

The NA61-SHINE apparatus provides high quality measurements of both energy loss (dE/dx) and time of flight (see Fig. 2). These measurements allow for particle identification over a large range of momentum: dE/dx alone is used to identify particles below 1 GeV/c and in the relativistic rise region of the Bethe-Bloch curves, while time-of-flight alone can be used between 1 and 6 GeV/c. The combination of both measurements provides a powerful separation of the different particle species over a wider momentum range.

Data were taken in 2007⁵ and again in 2009 after a major readout upgrade for incoming protons of 31 GeV/c momentum (corresponding to the T2K beam momentum), using both a thin Carbon target (4% of interaction length) and a full size replica of the T2K target (1.9 interaction length). For the cosmic ray program, data were taken for incoming pions of 158 and 350 GeV/c momentum.

The large acceptance of the NA61-SHINE apparatus covers the relevant phase space of both T2K and Auger experiments. As an example, Fig. 3 compares the absolute (corrected) π^+ distribution in the $\{p, \theta\}$ (θ is the production angle with respect to the beam direction) phase space measured by NA61 with the thin Carbon target and that of π^+ 's from the primary interaction producing neutrinos in the far detector of the T2K experiment obtained from the T2K beam simulation.

2.2 Preliminary spectra for positive and negative pions

The proton on Carbon data at 31 GeV/c from the 2007 pilot run have been used to produce preliminary spectra of both negative (up to 15 GeV/c momentum) and positive (up to 10 GeV/c momentum) pions in angular bins of 60 mrad. Differential cross-sections for different angular bins are shown in Fig. 4 and Fig. 5 respectively. Only statistical errors are shown, while results are still quoted with 20% systematic errors coming from the current level of disagreement obtained

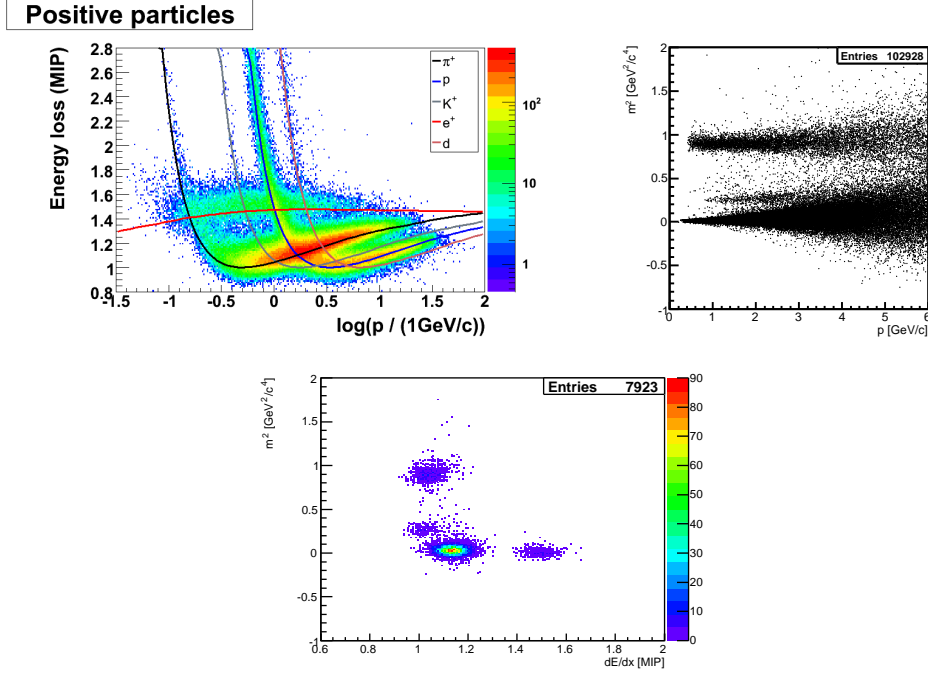


Figure 2: Energy loss versus momentum (left) and mass squared versus momentum spectra (right) for positive particles. Combined energy loss and time-of-flight measurements for all particles in the momentum range $[2, 2.5]$ GeV/c (bottom).

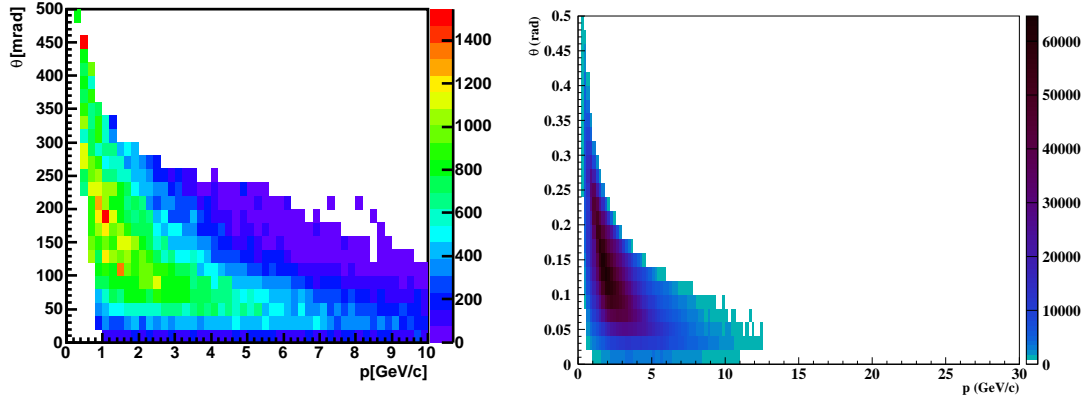


Figure 3: Absolute π^+ spectrum in the $\{p, \theta\}$ phase space measured in NA61 (left). Distribution of π^+ 's producing neutrinos in the far detector of the T2K experiment.

when comparing results from different analysis procedures in some bins.

Three procedures have been developed for the analysis: the negative hadron analysis, the dE/dx analysis below 1 GeV/c momentum and the combined $ToF-dE/dx$ analysis starting from 0.8 GeV/c , which is necessary for the π^+ spectra. The three procedures give consistent results within the quoted systematic errors for the negative pion analysis (see Fig. 4) and continuity is observed between the procedures used for the positive pion analysis (see Fig. 5).

The thin Carbon target results also include the determination of the absolute inelastic cross-section (used for normalization) of proton on Carbon at 31 GeV/c , and preliminary comparisons with different models such as GiBUU⁷, Geant4¹¹ and FLUKA-standalone. Work is currently performed to lower the quoted systematic errors.

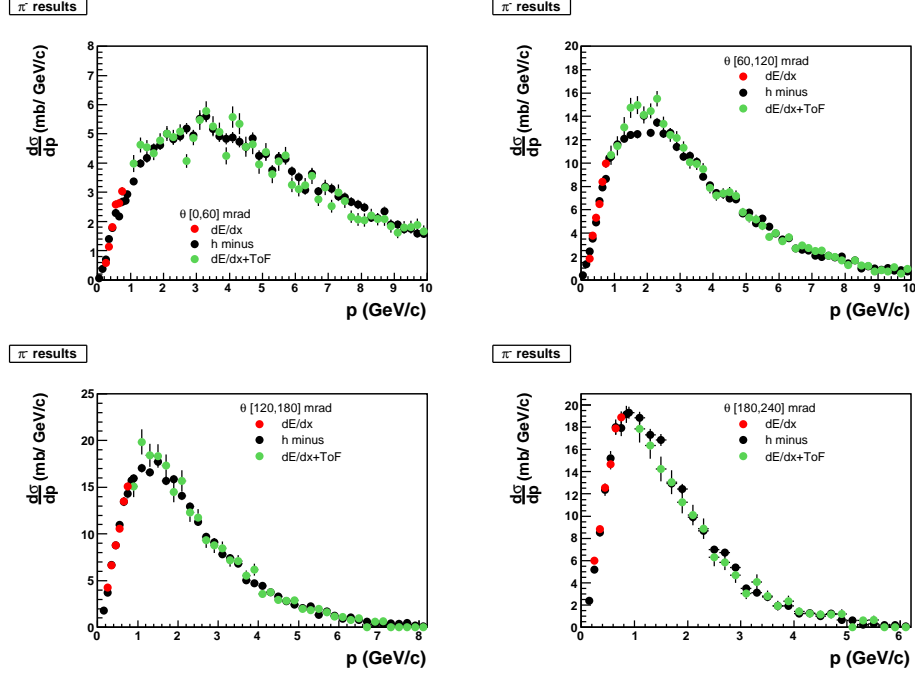


Figure 4: Differential cross-section for negative pions in four different angular bins (mentioned on plots). Markers correspond to different analysis procedures.

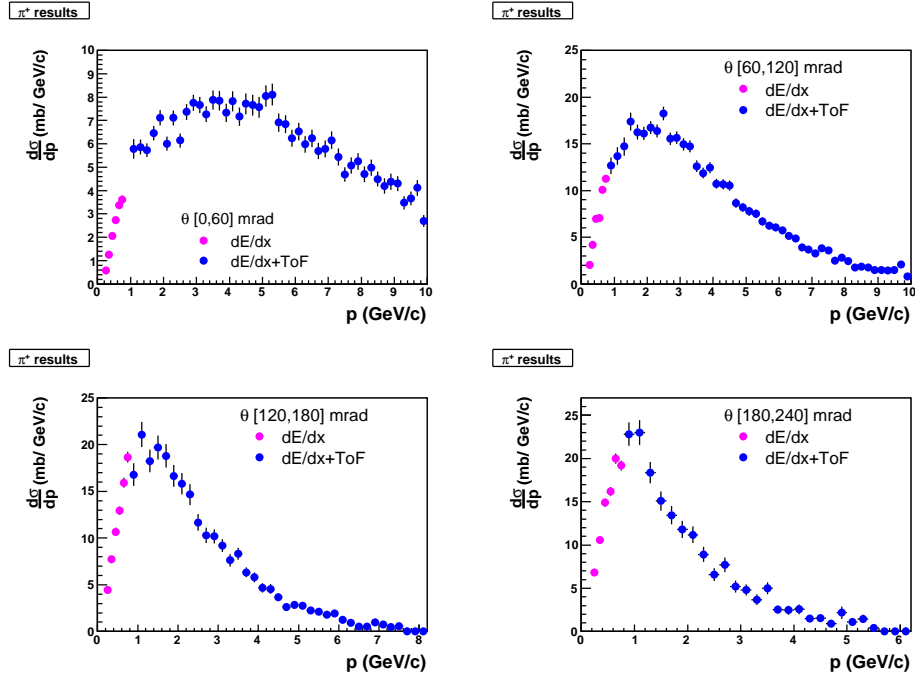


Figure 5: Differential cross-section for positive pions in four different angular bins (mentioned on plots). Markers correspond to different analysis procedures.

3 NA61 data for the T2K neutrino flux predictions

JNUBEAM (release 10a) is the T2K beam simulation¹ program. It has been used to predict fluxes for the four different neutrino species (ν_μ , $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$) at both T2K near and far

detectors. Fig. 6 shows total fluxes for all species at the far detector, as well as contributions from different parent particles for ν_μ and ν_e species.

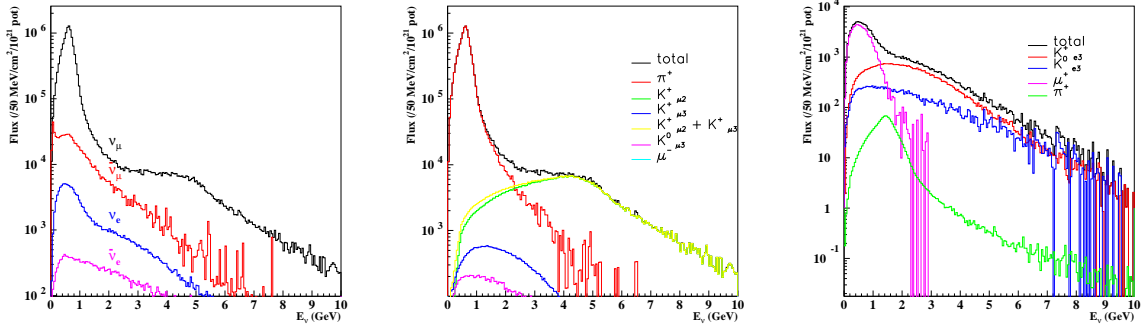


Figure 6: Neutrino fluxes for all species (ν_μ , $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$) at the far detector (left). Parent contributions to ν_μ (middle) and ν_e (right) fluxes at the far detector.

Contributions to the neutrino fluxes have been defined according to the NA61 measurements. *In-target* and *out-of-target* contributions refer to the measurements with the full size T2K replica target. *Indirect* and *direct* contributions refer to the measurements with the thin target in which only primary interactions are measured.

The *in-target* contribution comes from neutrino parents produced inside the target (from primary or secondary interactions), as well as from neutrino parents (such as muons) produced in the decay of particles originating from the target ($\sim 5\text{--}10\%$ of the contribution). Apart from decays out of the target, this contribution corresponds to what is measured with the long target. The *out-of-target* contribution accounts for neutrino parents produced in re-interactions in the other elements of the beam line (magnetic horns in particular).

The *direct* contribution comes from neutrino parents produced in the primary interaction, as well as from parents produced in the decay of those secondary particles. Apart from decays, this contribution corresponds to what is measured with the thin target. The *indirect* contribution accounts for parents produced in secondary interactions in and out of the target.

As shown in Fig. 7, the ratio of the out-of-target contribution to the total contribution is $\sim 10\%$ at peak energy for both ν_μ and ν_e species. The equivalent ratio between indirect and total contributions is $\sim 40\%$ at peak energy for both ν_μ and ν_e . This conclusion stresses the importance of the replica target measurements: providing tracks with momentum and angle (with respect to the beam direction) at exit point on the target surface will allow to predict directly a fraction of the neutrino flux at both near and far detectors as high as $\sim 90\%$ for both ν_μ and ν_e components.

Studies showed variations (both in shape and normalization) of the absolute neutrino fluxes as a function of the neutrino parent exiting point position on the target surface, as well as of the beam profile used in the simulation. Those considerations lead to a binning of the replica target data consisting in six equidistant longitudinal bins and three to four radial bins.

The NA61-SHINE thin target measurements can provide pion and kaon production cross-sections as direct input to the T2K beam simulation. In this case, still $\sim 40\%$ of the neutrino fluxes would require using models for secondary interactions. Due to the limited azimuthal acceptance of NA61-SHINE, the replica target data cannot be used as a direct input to the simulation on an event-by-event basis. However, they can be used to re-weight the beam Monte-Carlo using the event generators of the T2K beam simulation within the NA61-SHINE simulation chain. In this case, 10% of the neutrino fluxes would still require using models to predict secondary interactions outside the target. A method has been developed to propagate those re-

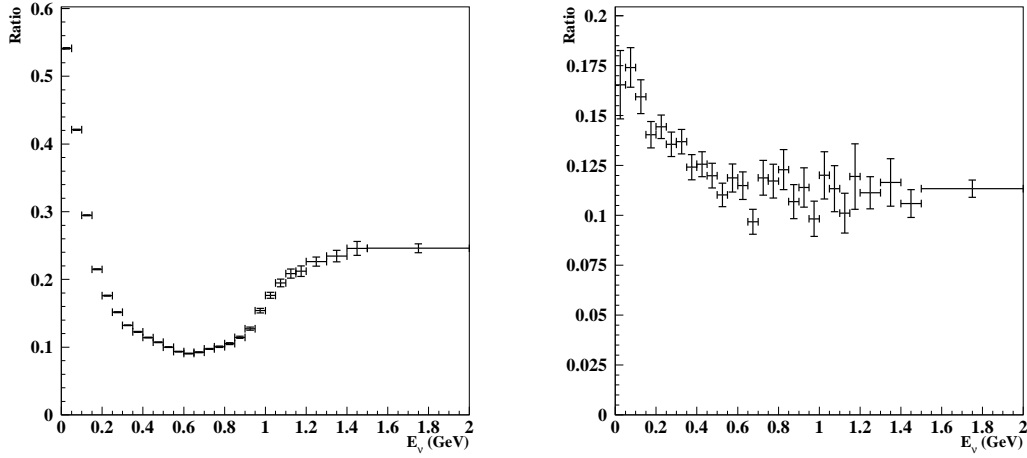


Figure 7: Ratio of the out-of-target contribution to the total contribution for ν_μ (left) and ν_e (right) components at the far detector.

weighting factors (and associated statistical and systematic errors) from the $\{p, \theta\}$ phase space (in longitudinal and radial bins) of relevance in T2K, to the neutrino flux predictions.

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